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Physical Modelling in Geotechnics

Small-scale model tests on the formation of compaction pile using controlled grading aggregates

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ABSTRACT: This paper demonstrates the effectiveness of controlled grading aggregates as an alternative material to the sand compaction pile method (SCP), which is one of the most typical ground improvement methods in field practice, particularly in soft clay profiles. However, the SCP has faced difficulty due to the supply shortage and the corresponding price surge of sand. This study evaluates the performance of the new material to form a marine aggregate compacted pile (MACP) using small-scale model tests to investigate its potential application in comparison with SCP. The compaction piles are examined in four cases composed of two clay models at various pre-consolidated pressures of 60 kPa and 100 kPa. The experimental data reveal that the bulb formation size of the conventional SCP and the proposed MACP are deemed comparable. Controlled grading aggregates in MACP have a higher internal friction angle than marine sand in SCP, which yields a more significant bearing capacity.

Keywords: sand compaction pile, controlled grading aggregate, bulb formation, improvement soft ground

1 INTRODUCTION

The sand compaction pile (SCP) method is established in Japan by constructing composite ground consisting of compacted sand piles to improve soft grounds (Ezoe *et al.*, 2019). SCP offers improved bearing capacity of foundation systems for onshore superstructures including roads and buildings, and offshore applications such as ports, and coastal disaster prevention facilities. This method utilizes casing pipes as a lifting or driving device (non-vibratory hammer) for penetration, withdrawal, and compaction as shown in Fig. 1 (Harada and Ohbayashi, 2017). For instance, a 1.2-m diameter casing is employed to build a 2.1-m enlarged diameter well-compacted sand piles, hence densifying the surrounding soft ground. As a result, the SCP yields superior bearing capacity, higher shear resistance, reduced residual settlement, and liquefaction resistance (Barksdale and Bachus, 1983; Bong *et al.*, 2018).

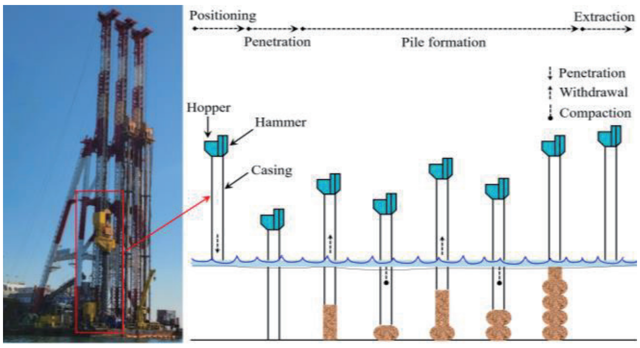


Fig. 1. Installation procedure for non-vibratory SCP method.

In recent decades, the shortage of natural sand production has caused price inflation. Furthermore, sand mining from the ocean has also addressed the environmental impacts such as its detrimental effects on biodiversity underwater and coastal erosion. Hence, the granular compaction pile (GCP) method has been introduced to address the drawbacks of SCP (Lee *et al.*, 2010). The GCP utilizes crushed stone and gravel, which hold better bearing capacity and drainage than sand. However, when crushed stone piles are applied on super soft clay ground offshore, the bulging failure occurs at the pile tip due to uneven bulb formation and eventually collapses (Kim, 2009). Because of this, the GCP is limited to onshore applications and not practical offshore. The uniformity of compacted pile bulbs is deemed critical to ensure the bearing capacity of the compaction pile.

In line with the method development, a marine-controlled aggregate compaction pile (MACP) has been proposed using new material preparation and casing pipe design (Kim, 2021). The particle size distribution of the aggregate material for the compaction pile is controlled such that the grading contains the coarsest material in crushed stones and the finest grain material in marine sand as shown in Fig. 2, which improves installation execution and resistance to clogging. Furthermore, the controlled grading aggregate exhibits a higher internal friction angle than sand and even crushed stone with the same maximum grain size, yielding better-improved bearing resistance of compaction pile.

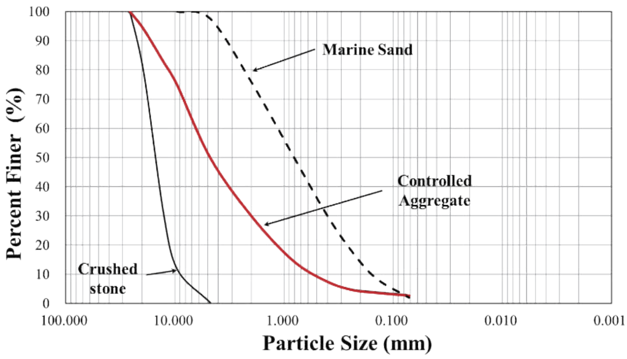


Fig. 2. Particle size distribution.

To examine the quality of the controlled grading aggregates as a substitute material for sand, a series of small-scale model tests was performed to reveal the bulb formation mechanism of both compaction piles (SCP and MACP).

2 PHYSICAL MODELLING

2-1 Design of Model Tests

The testing system employed in this study consists of a cylindrical steel model container, linear servo actuator (main actuator), rigid rod, casing pipe, driving hammer, and guide rail as presented in Fig. 3. Model casing size was determined from the prototype casing pipe used in Chosuk No. 1 ship with a scaling ratio of 1:6 to simulate field procedures of the SCP method as depicted in Fig. 1. The model casing was fabricated using aluminum alloy, featuring 208 mm external diameter (1.2 m in prototype scale), 200 mm internal diameter, and 540 in depths.

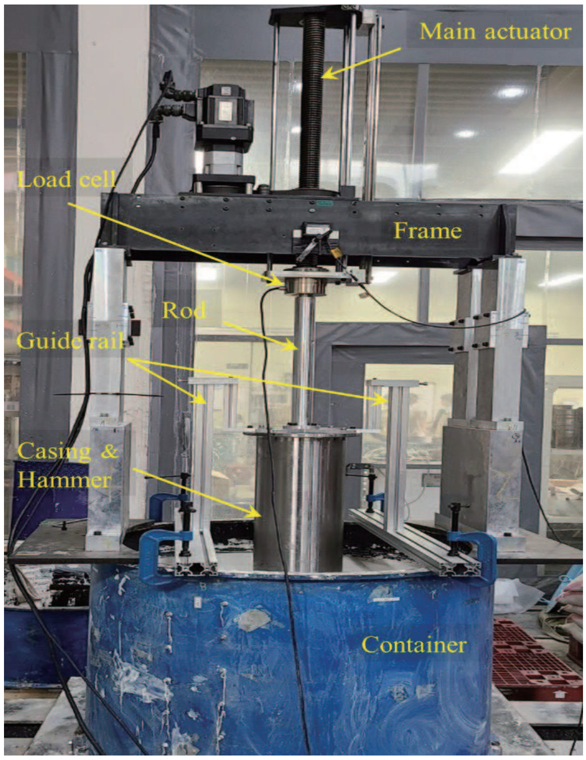


Fig. 3. Small scale sand pile compaction experimental setup.

In the operation of the model tests, the driving hammer was designed to move independently with the casing pipe. For example, the hammer was rigidly fastened on the casing ledge during penetration and withdrawal. And the hammer was detached from the casing during compaction to compress the infilled materials in form of either sand or aggregates to form a layer of the pile bulb. The casing-hammer system was operated by the main actuator to simulate the process of penetration, extraction, and compaction depicted in Fig. 1. Guide rails secure the verticality of the casing pipe during the entire experiment.

A load cell (TCLK-NA 50 kN) was attached directly below the main actuator to measure the compaction load developed during the course compaction stage. The load-displacement curve in each pile bulb will be discussed in this paper.

2-2 Testing program

The testing program was designed to operate various types of materials and different strength of the clay beds. Four model tests at normal gravity level were conducted as shown in Table 1. Marine sand and controlled grading aggregates were used as the infilled materials for compaction piles (see Fig. 2 and Table 2). In addition, model clay beds were pre-consolidated at 60 kPa and 100 kPa. (see Table 1). 350-mm diameter compacted piles having a depth of 500 mm were formed, corresponding to a target replacement rate of 15.1%.

Table 1. Testing conditions.

Test ID	Pile type	Pre-consolidated pressure (kPa)	Replacement area ratio (%)	Pile depth (mm)
S-100	Sand	100	15.1	500
A-100	Aggregate			
S-60	Sand	60		
A-60	Aggregate			

2-3 Clay Specimen

A 50-mm-thick silica sand base layer was placed on a geotextile mat resting at the bottom of the container. The Kaolin clay powder and water were thoroughly mixed in a 210-liter vacuum mixer to achieve 140%-moisture-content clay slurry, which is about two times the liquid limit. Using an extended casing above the container, the clay was filled up to the desired elevations (853 mm for S-100, and A-100, and 821mm for S-060, and A-060). Table 2 summarizes the geotechnical properties of materials used in this study.

Table 2. Geotechnical properties of materials used in this study

Soil Property	Kaolin clay	Marine Sand	Controlled Grading Aggregates
Mineral	Kaolinite		
Source	Indonesia	Republic of Korea	Republic of Korea
Specific gravity, G_s	2.53		
Liquid Limit, LL (%)	67.99		
Plastic Limit, PL (%)	37.57		
Plasticity Index, PI (%)	30.42		
Grain size (mm)		$d_{10} = 0.16$	$d_{10} = 0.54$
		$d_{50} = 0.8$	$d_{50} = 4.8$
		$d_{60} = 1.16$	$d_{60} = 6.4$
Angle of friction, ϕ (°)		37.1	54.7

The clay specimens were pre-consolidated at 60 kPa and 100 kPa for 240 hours. Such overburden pressures were incrementally increased until the settlement plateaued at the final pre-consolidated pressures (S-100, A-100; 100kPa, S-060, A-060; 60kPa). Hence, the clay beds were used to simulate marine soft ground.

Miniature cone penetrometer tests were employed to characterize the undrained strength of clay beds just before the bulb formation test of compaction piles. The miniature cone was penetrated at a rate of 1 mm/s from the ground surface up to a depth of 350 to 400 mm.

2-4 Testing Procedure

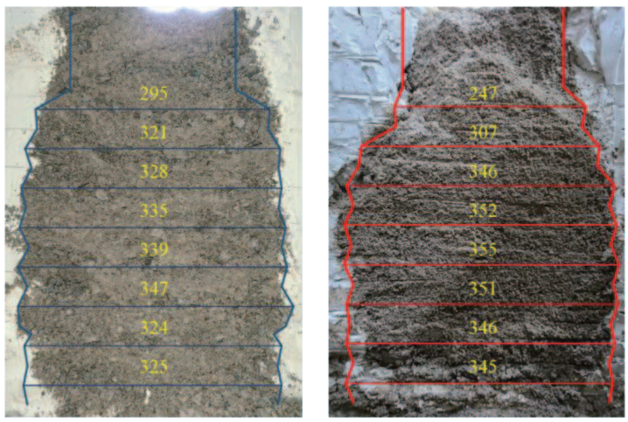
The compacted pile bulb formation scale model experiment mimics the field construction procedures depicted in Fig. 1. First, the pile casing-hammer was penetrated 500 mm into the soil surface. After installation, the hammer was drawn out of the casing and left the casing open to allow the infilling of material for the compaction pile formation. Then the casing was slightly extracted about 150 mm upward from the infilled soil bed. Subsequently, the hammer was reassembled into the casing and driven 100 mm downward to compress the infilled material into the soil bed. As a result, 350-mm enlarged diameter bulbs with a height of 50 mm were formed at each layer. This process was done on top of the previous bulb on eight occasions, however, the topmost layer was filled with 100-mm uncompacted material to complete a 500-mm deep compaction pile. Finally, another cone penetrometer was employed to measure the ground strength after the bulb formation test of the compacted pile.

3 RESULT AND DISCUSSION

3-1 Compacted pile bulbs

The 500-mm deep compaction piles (SCP and MACP) were formed by compacting eight 50-mm layers of enlarged bulbs and 100-mm uncompacted materials to fill until the ground surface. Pile cross-sections of SCP and MACP are shown in Fig 4(a) for case A-100 and Fig 4(b) for case S-60. The enlarged diameter bulbs were measured from the outer walls of the container at respective layers. Compacted bulbs in the controlled grading aggregate revealed pile enlargement of 295 to 347 mm and 247 to 355 mm in sand piles.

Although cases A-100 and S-060 were formed with different materials and varying pre-consolidated pressures, both tests reveal the uniform formation of the bulb along its depths. The diameters from the 6th to 8th layers of the bulbs (located near the ground surface in Fig. 4) were reduced compared with the deeper layers because of uncompacted grounds. Generally, the bulb shape of the compacted aggregate piles and sand piles were similar. Additionally, clay clogging in compaction piles was not observed in the cross-sections.



(a) A-100 (b) S-60

Fig. 4 Compacted pile bulb formation: (a) A-100, and (b) S-60.

3-2 Compaction load

The maximum compaction loads to form the enlarged bulbs in each layer were derived from the loadcell recordings as plotted in Fig. 5. Deeper sections of the compaction piles registered greater loads. It is worthy to note that for case A-100, the required load would exceed the load cell maximum capacity at the first layer, so the compaction was done until 70 mm instead of 100 mm. The missing compaction data in between is linearly estimated denoted dashed line in Fig. 5 for A-100.

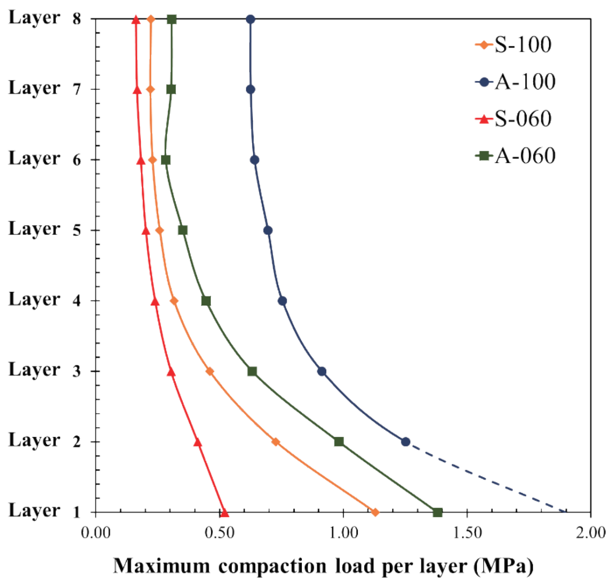


Fig. 5 Maximum compaction load curves.

The magnitudes of the compaction load were greatest in the deepest bulb layer and decreased with increasing level of bulb formation until reaching a plateau as the bulb nears the ground surface. Such large compaction loadings registered at the 1st and 2nd layers were attributed to the increasing earth pressure present at greater depths as well as the closeness to the bottom boundary.

In consideration of the pre-consolidated pressures applied to the clay, compaction load was most significant in A-100, A-060, S-100, and S-060 succession. This indicates that the compaction load profiles can translate to the bearing capacity of MACP outweighing the capacity of SCP.

4 CONCLUSIONS

This study simulates the actual compaction pile construction procedure to evaluate the performance of the controlled grading aggregates in forming compacted piles. A series of small-scale model tests was undertaken at a standard gravity setting to examine the bulb formation quality, and compaction load translating to the bearing capacity of MACP and SCP. Through the experimental results, the following can be deduced:

(1) The bulb formation of controlled grading aggregates for MACP forms uniformly well-compacted piles and falls in good agreement with that of the SCP. The enlarged diameters achieved in A-100 and S-60 for the 1st to 5th layers are within marginal differences. Additionally, the clogging of clay into the pile body was not observed in both compaction piles.

(2) The compaction loads are greatest in the deepest bulb layer and decrease as the bulb nears the ground surface due to the concentration of earth pressures at greater depths. MACP compaction load magnitudes outweigh the loading registered in SCP translating to superior bearing capacity.

(3) Controlled grading aggregates contain a higher internal friction angle than that of marine sand and crushed stone. Consequently, the compaction pile formed using the new material, controlled grading aggregates, could yield better performance than the sand compaction pile.

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REFERENCES

Barksdale, R. D., and Bachus, R. C. 1983. Design and construction of stone columns. *Report No. FHWA/RD-83/026, National Technical Information Service*.

Bong, T. H., Kim, B. I. and Han, J. T. 2018. Estimation of Ultimate Bearing Capacity of SCP and GCP Reinforced Clay for Laboratory Load Test Data. *Journal of the Korean Geotechnical Society* 34(6): 37-47.

Chun, B. S., Kim, W. C. and Jo, Y. W. 2004. Comparative Study on the Prediction Method of Bearing Capacity for Single Stone Column. *Journal of the Korean Geo-Environmental Society* 5(1): 55-64.

Ezoe, A., Harada, K. and Otani, J. 2019. Sand Compaction Pile Method and Its Applications. *Int. J. of Geosynth. and Ground Eng*. 5(24) https://doi.org/10.1007/s40891-019-0175-9

Harada, K. and Ohbayashi, J. 2017. Development and improvement effectiveness of sand compaction pile method as a countermeasure against liquefaction. *Soils and Foundations* 57(6): 980-987, https://doi.org/10.1016/j.sandf.2017.08.025.

Kim, I. G., Chosuk construction co., Korea port engineering co. Sekwang Engineering Consultants Co., and Eunsung Onshore/Offshore Marine & Construction Co. 2021. Marine soft ground improvement method using ball-type casing, automatic air control device and aggregate for mechanical stabilization. Korea Patent No. 10-2288513-0000

Kim, J. H. 2009. The Experimental Study on Composite Ground Behavior and Aspect of Clay Gone through Compaction Pile of Recycled Aggregate Compaction Piles. *M. S. Dissertation, Hongik University*, Seoul, Korea.